Search for Quark Deconfinement: Strangeness Production in *pp*, *dd*, $p\alpha$, and $\alpha\alpha$ Collisions at $\sqrt{s_{NN}} = 31.5$ and 44 GeV

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Relative yields of ϕ and charged K mesons are measured as functions of charged multiplicity in the central rapidity region for *pp*, *dd*, $p\alpha$, and $\alpha\alpha$ collisions at $\sqrt{s_{NN}} = 3.15$ and 44 GeV. No anomalous strange-particle production is observed in $\alpha\alpha$ reactions relative to *pp* even at large multiplicities corresponding to events comprising less than 3.6×10^{-4} of the inclusive cross section.

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The possibility that "collapsed" nuclei might be produced or exist in nature goes back to early suggestions by Feenberg and Primakoff[1] and Lee and Wick.[2] With the introduction of QCD as the basic theory of strong interactions, it is now believed[3] that at sufficiently high nuclear density the deconfinement of the nucleon constituents can take place with the formation of a new state of matter, the quarks and gluons now confined to the larger nuclear volume. It has also been speculated that the conditions for deconfinement may be realized in ultrarelativistic "head-on"[4] nucleus-nucleus collisions,[3] and nucleon-nucleon collisions.[5,6]

The number of strange quarks in the deconfined phase may be enhanced relative to the number of up and down quarks,[3,7] with a resultant increase in the production of strange particles relative to nonstrange particles. It is claimed[7] that the equilibrium density of the strange quarks in the deconfined state is primarily reached through $gg\rightarrow s\bar{s}$ reactions whose mean reaction time is shorter than the lifetime of the deconfined state. This work reports on a search for such effects in very high-multiplicity head-on $\alpha\alpha$ collisions at the CERN ISR.

A basic difficulty is that the expected deconfinement phase transition cannot be described by perturbative QCD, so that crude models must be the basis for any estimates. However, our method to search for deconfinement is predicated on only two qualitative requirements, that the deconfinement probability increases with containment volume and energy density. A larger volume will increase the probability that a thermodynamic equilibrium will be attained, as well as reducing the effect of energy loss due to pion radiation from the surface of the deconfined state, which has been proposed as the principal means by which the deconfined state loses energy.[8] Our experimental technique is to examine the yields of particles as a function of A and to use multiplicity variation as a measure of the energy density. Note that a search for deconfinement in a *pp* collision alone suffers from the fact that an "ordinary" change in the K/π ratio with multiplicity cannot be predicted from QCD, so that there is no way of defining an "anomalous" ratio. Thus we search for an A-dependent effect that is greater at high multiplicity than at low multiplicity. Accordingly we compare the production of π, K, and ϕ

mesons for *pp*, *dd*, $p\alpha$, and $\alpha\alpha$ collisions as a function of multiplicity at $\sqrt{s_{NN}} = 3.15$ and 44 GeV using the axial-field spectrometer.[9]

Most models[3] of deconfinement predict the phase transition to occur at nuclear energy densities of the order of a few to ten times the normal nuclear density of 0.15 $\mathrm{GeV/fm^3}$. The detection of the deconfinement transition requires sufficient energy deposition, time to ensure some thermalization, a large enough signal, and the ability to calculate *ordinary* signals that might simulate the deconfinement. There are several estimates for the energy density reached in head-on nucleus-nucleus collisions. They, in turn, depend on estimates of the formation time, the rapidity density in *A-A* collisions, and the mean energy per particle $\langle E\rangle$. One estimate given by Bjorken[10] for the energy density ϵ,

$$\epsilon = \langle E\rangle (dn/dy)_{AA}/\pi r^2 ct_0,$$

where t_0 is the formation time, assumes that a head-on *A-A* collision deposits an energy $\langle E\rangle (dn/dy)_{AA}$ into a contracted volume equal to the product of the cross-sectional area πr^2 by ct_0. With use of the measured value[11] of $(dn/dy)_{\alpha\alpha} = 3.74$ (charged+neutral), $\langle r^2\rangle^{1/2} = 1.7$ fm for He,[12] $\langle E\rangle = 0.4$ GeV, Kisielewska's[13] largest value for $ct_0 = 0.5$ fm, and the fact that we study $\alpha\alpha$ events with multiplicities ≥ 4.4 times the mean multiplicity, we find that $\epsilon = 1.45$ $\mathrm{GeV/fm^3}$. If we assume $\epsilon \sim A^{1/3}$ for central collisions,[10] this calculated energy density for the high-multiplicity $\alpha\alpha$ collisions is approximately what is obtained for a central oxygen-oxygen collision. Another estimate, given by Gyulassy and Matsui,[14]

$$\epsilon = 1.6[(dn/dy)_{AA}/\pi r^2 ct_0]^{4/3}$$

predicts $\epsilon = 8.9$ $\mathrm{GeV/fm^3}$ for the highest-multiplicity $\alpha\alpha$ events. The $\frac{4}{3}$ power comes about from the calculation of the rapidity density after the hydrodynamical expansion of the deconfined state, whereas the Bjorken formula is applied at formation time. These different estimates for ϵ reflect the current state of theoretical uncertainty.

It is also required that the signals must be comfortably larger than the signals without deconfinement. There are, of course, several well-known nuclear effects which might simulate a signal and can result in differences in the relative number of *K*'s and π's as one goes from *pp* to $\alpha\alpha$ collisions: (1) *nn* and *pn* collisions now occur in addition to *pp*. (2) The *K* or π yields at a fixed p_t vary as A^n with *n* a function of both p_t and particle type.[15] For example, for a $p\alpha$ collision enhancements of K/π yields of $\approx 20\%$ occur, and of K^-/K^+ yields of $\approx 5\%$. (3) One may also expect to find variations with multiplicity that come about because high-multiplicity events favor small-impact-parameter collisions so that effect of rescattering, absorption, or energy loss can change the observed ratios as a function of multiplicity. Thus one will need *A* dependences at a given multiplicity comfortably larger than 20% to observe new phenomena.

The apparatus is described in detail in Ref. 9. The beam intersection was surrounded azimuthally by a cylindrical array of 44 scintillation ("barrel") counters covering a pseudorapidity $|\eta| \leq 1.7$ and a cylindrical drift chamber consisting of 82 sectors azimuthally distributed about the beam axis, with each sector containing 42 wires. The chamber covered $|\eta| \leq 1.6$ and 328° azimuthally. The apparatus was situated in an axial magnetic field of 0.5 T. Charged-particle coordinates (x,y) transverse to the beam direction (z) were measured by drift time and the *z* coordinate by charge division in the drift chambers. The charge measurement is a measure of dE/dx which is used for particle identification. Downstream (4.5 m) from the intersection in each beam direction were scintillation counters (beam-beam counters) covering polar angles from 1.2° and 6.0°. Two types of triggers were employed in the data acquisition: (1) minimum bias (MB), which required one or more barrel counter hits or a coincidence between the beam-beam counters; (2) high multiplicity (HM), which required ~ 15 or more of the barrel counters to fire. A summary of the beams, trigger types, and number of triggers is given in Table I.

Events and tracks selected for particle identification in the drift chamber undergo several quality and geometrical cuts: (1) A primary vertex is found and the track is associated with that vertex. (2) $|\eta| \leq 0.8$. (3) The number of *z* measurements $N_z \geq 20$. (4) Track length ≥ 47 cm. (5) $0.2 < p < 2.0$ GeV/*c*.

A dE/dx-momentum scatter plot manifests clear bands of pions, kaons, and protons.[16] A track is identified as a pion if $dE/dx \leq 2.0$ times minimum ionizing and $0.2 \leq p \leq 0.3$ GeV/*c*. The lower momentum limit is chosen to be well above the minimum momentum acceptance of the spectrometer (≈ 0.07 GeV/*c*) and the upper limit to be well removed from the kaons. Since there is no contamination from kaons the pions can be identified on an event-by-event basis. This is not the case for the kaons where in order to increase our sample we accepted kaons which fell in a dE/dx-momentum band where there is some contamination from pions and protons. The number of kaons is extracted as follows. Tracks are required to have $dE/dx \geq 1.28$ times minimum ionizing corresponding to *K*'s with $p \lesssim 0.65$ GeV/*c*. The lower momentum limit for the *K*'s is ≈ 0.25 GeV/*c* corresponding to the range limit. The momentum distribution of the tracks for all the events in a chosen dE/dx interval manifests peaks corresponding to π's, *K*'s, and protons. The number of kaons is determined by subtraction of the

TABLE I. Summary of the number of multiple-kaon events for the various beams and triggers (MB = minimum bias, HM = high multiplicity). $\langle N \rangle$ = mean multiplicity. The numbers in parentheses are the numbers expected on a statistical basis from the number of single-kaon events.

Beam ($\sqrt{s}$)	$\langle N \rangle$	Events (10^3)	K^+K^+	K^-K^-	K^+K^-	$3K$	ϕ/K^+K^- (%)
pp (MB-31)	6.5	124	14(18.3)	13(13.4)	70(31.4)	0(0.8)	12.3 ± 6.2
pp (MB-44)	7.2	118	9(17.0)	15(11.9)	73(28.4)	1(0.9)	11.7 ± 6.3
dd (MB-31)	7.3	48	5(7.7)	5(6.8)	40(14.5)	0(0.4)	2.6 ± 8.3
dd (HM-31)	24.0	11	13(13.9)	9(12.7)	35(26.5)	2(1.8)	6.3 ± 11.7
$p\alpha$ (MB-31)	7.4	88	10(17.5)	13(14.6)	55(32.0)	2(1.1)	12.5 ± 7.6
$p\alpha$ (MB-44)	8.5	137	28(33.8)	26(26.1)	133(66.0)	7(2.0)	13.8 ± 4.6
$p\alpha$ (HM-44)	25.8	71	71(96.2)	58(84.4)	242(180.2)	18(13.9)	10.8 ± 3.1
$\alpha\alpha$ (MB-31)	10.2	176	64(65.9)	36(50.2)	213(114.1)	5(5.3)	16.2 ± 3.8
$\alpha\alpha$ (HM-31)	30.7	32	62(70.4)	48(54.6)	130(124.0)	11(10.6)	13.6 ± 4.8

contributions from the π's and protons ($\approx 15\%$) from the K peak.

As expected from the known operation of the chambers the $\langle \chi^2 \rangle$ per track increases with multiplicity and $\langle N_z \rangle$ decreases with multiplicity since neighboring tracks affect the determination of the coordinates. In order not to introduce any distortions in the multiplicity scale, especially at the higher multiplicities, we do not impose the stringent requirements imposed for particle identification and only require nine x,y digitizings to determine the presence of a track. This is how the multiplicity is defined throughout this paper and it is the mean of this multiplicity that is listed in Table I for the various beams and triggers. This mean multiplicity at $\sqrt{s_{NN}} = 3.15$ GeV for the $\alpha\alpha$ minimum-bias trigger corresponds to the measured[11] *charged* central rapidity density of 2.59.

The fractions of π's and K's relative to all the tracks passing the quality cuts are presented in the following fashion in Figs. 1 and 2. (Note the displaced zero.) The events are grouped together in ten bins each containing 5 units of multiplicity (0–4 up to 45–49 tracks). In order to compare the data points with the least confusion the plots are displaced vertically for the various beams, and displaced horizontally when data were taken at two energies for the same beam configuration. To guide the eye, smoothing curves have been fitted to the p-α data and shown on all plots. By studying the $\bar{p}p$ reactions, comparing $\alpha\alpha$ data taken two years apart, and comparing our MB and HM data

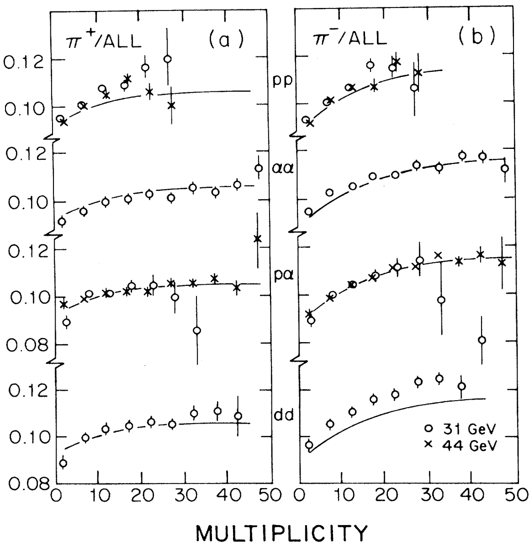

FIG. 1. Fraction of tracks identified as π's for pp, $\alpha\alpha$, $p\alpha$, and dd reactions. (a) π^+, (b) π^-.

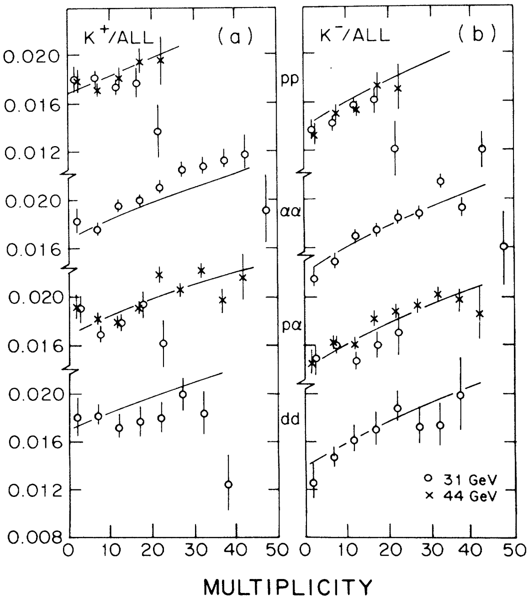

FIG. 2. Fraction of tracks identified as kaons for pp, $\alpha\alpha$, $p\alpha$, and dd reactions. (a) K^+, (b) K^-.

at multiplicities where they overlap, we estimate our systematic errors to be $\approx 10\%$. A study of the momentum distributions shows a 5% variation in the mean momentum with multiplicity over the full multiplicity range covered in this paper. A determination of the K/π ratio for our MB pp data at $y=0$ and $p_t = 0.34$ GeV/c yields a value of $(10.9 \pm 0.7)\%$, in excellent agreement with the value published by Alper *et al.*[17]

Figure 1 shows that the fraction of π's as a function of multiplicity is similar for all the reactions with the exception of the greater fraction of π^+'s ($\approx 5\%$) for the pp reaction, and the larger fraction of π^-'s ($\approx 10\%$) for the dd reaction. These data show that the differences between various data sets are small. The K^- data [Fig. 2(b)] show little difference between data sets. The K^+ data [Fig. 2(a)] show an increase in slope as one progresses from dd to $p\alpha$ to $\alpha\alpha$ reactions. Averaging over the first and last three multiplicity intervals in the $\alpha\alpha$ data, we observe $(24.4 \pm 1.0)\%$ and $(30.0 \pm 1.4)\%$ rises in K^+/all and K^-/all, respectively, with multiplicity. Rises of $(8.4 \pm 0.2)\%$ and $(12.7 \pm 0.9)\%$ with multiplicity are also observed for protons and antiprotons (not presented here), respectively. The rises in K^+/π^+ and K^-/π^- are smaller being $(14 \pm 1)\%$ for both. These changes in yield with multiplicity represent an expected systematic effect since we know from these and previous[11,18] studies that there is a change in the shape of the momentum spectra of charged particles as the event multiplicity is varied.

To search more sensitively for the presence of anomalous strangeness production, we have searched for an enhancement in the number of multiple-kaon events. Since it is now desirable to identify K's event by event, we require $dE/dx > 1.7$ times minimum ionizing where the contamination from π's and protons is $\approx 3\%$. Table I summarizes the number of double- and triple-kaon events for each beam and trigger configuration. The numbers of multiple-kaon events expected statistically on the basis of the number of observed single kaons are shown in parentheses. No excess is observed for the like-sign kaon pairs where a slight negative correlation is indicated. The excess in the K^+K^- is due to associated strangeness production. This excess decreases as one goes from MB pp to HM $\alpha\alpha$ as expected, since the oppositely charged kaons can now arise from separate nucleon-nucleon collisions, e.g., within an $\alpha\alpha$ event.

Shor[19] has suggested that ϕ-meson production should be enhanced in a quark-gluon plasma since the Okubo-Zweig-Iizuka suppression is no longer present. The percentage of ϕ's per K^+K^- pair is summarized in Table I. The relative yields from all reactions and triggers appears to be the same.

We conclude from this comparison of dd, $p\alpha$, and $\alpha\alpha$ reactions at ISR energies that there is no evidence for anomalous strangeness production. At the highest multiplicities studied we are sensitive to 3.6×10^{-4} of the $\alpha\alpha$ inelastic cross section.

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[1] E. Feenberg and H. Primakoff, Phys. Rev. **70**, 980 (1946).

[2] T. D. Lee and G. C. Wick, Phys. Rev. D **9**, 2291 (1974).

[3] *Proceedings of the Bielefeld Workshop on Quark Matter Formation and Heavy Ion Collisions*, edited by M. Jacob and H. Satz (World Scientific, Singapore, 1982); *Proceedings of the Third International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Upton, New York, 1983*, edited by T. W. Ludlam and H. Wegner [Nucl. Phys. **A418** (1984)]; *Proceedings of the Fourth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Helsinki, Finland, 1984*, edited by K. Kajantie (Springer-Verlag, New York, 1985); E. V. Shuryak, Phys. Lett. **107B**, 103 (1981); J. Kogut *et al.*, Phys. Rev. Lett. **48**, 1140 (1982).

[4] We define a head-on collision as one in which all the nucleons are struck. A Monte Carlo calculation shows that this occurs at the 1% level in $\alpha\alpha$ collisions.

[5] A. K. Mann and H. Primakoff, Phys. Rev. D **22**, 1115 (1980).

[6] L. Van Hove, Phys. Lett. **118B**, 138 (1982).

[7] J. Rafelski and B. Müller, Phys. Rev. Lett. **48**, 1066 (1982); B. Müller, in *The Physics of the Quark-Gluon Plasma*, edited by H. Araki *et al.* (Springer-Verlag, New York, 1985).

[8] M. Danos and J. Rafelski, Phys. Rev. D **27**, 671 (1983).

[9] H. Gordon *et al.*, Nucl. Instrum. Methods **196**, 303 (1982); O. Botner *et al.*, Nucl. Instrum. Methods **196**, 315 (1982).

[10] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).

[11] T. Åkesson *et al.*, Phys. Lett. **119B**, 464 (1982).

[12] R. F. Frosh *et al.*, Phys. Rev **160**, 874 (1967).

[13] D. Kisielewska, to be published.

[14] M. Gyulassy and T. Matsui, Phys. Rev. D **29**, 419 (1984).

[15] D. Antreasyan *et al.*, Phys. Rev. D **19**, 764 (1979).

[16] T. Åkesson *et al.*, Nucl. Phys. **B203**, 27 (1982).

[17] B. Alper *et al.*, Nucl. Phys. **B100**, 237 (1975).

[18] W. Bell *et al.*, Z. Phys. C **27**, 191 (1985); A. Breakstone *et al.*, Phys. Lett. **132B**, 463 (1983).

[19] A. Shor, Phys. Rev. Lett. **54**, 1122 (1985).